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A technique is investigated for controlling the operating frequency and polarization of microstrip antennas. The control is achieved by the placement of shorting posts at appropriate locations within the antenna's boundaries. By changing the number and locations of the posts, the operating frequency can be tuned over a 1.5-to-1 range, and the polarization can be changed from horizontal to vertical, right-hand circular, or

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20. ABSTRACT (Cont'd)

left-hand circular. All these changes are obtained without significantly altering the input impedance or radiation patterns of the antenna and without increasing the complexity of the external microwave feed network. Also, the frequency and polarization can be electronically controlled by the use of microwave switching diodes for the shorting posts. Antennas that have two feeds and operate simultaneously in two orthogonal polarizations have been constructed with the capability to switch between linear and circular polarizations. Also, a thin, frequency-scanned array has been built with the frequency-agile microstrip elements.

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1. INTRODUCTION

The microstrip antenna has been shown to be an excellent radiator for many applications requiring only a narrow bandwidth. It is rugged and can be fabricated economically with standard printed-circuit techniques. As with other single-element antennas, a single microstrip radiator has a moderately broad radiation pattern, but arrays with high gain have been demonstrated.

In its simplest form, the microstrip antenna radiates linearly polarized signals over a bandwidth of 1 to 2 percent. By modifying its geometry, it is possible to obtain circularly polarized radiation or a shift in the operating frequency. Since these techniques require permanent physical changes to the antenna, they are not amenable to electronic control of the antenna's performance. The antenna's performance can be electronically controlled by varactors or by variable length transmission lines. Varactors require a precise bias voltage control, and switched length transmission lines require space outside the basic microstrip antenna's boundaries. These are potential disadvantages and can be overcome by a simpler control mechanism such as shorting posts (e.g., switching diodes) at appropriate points within the strip boundary. By changing the number and location of the shorting posts, both the frequency and polarization of the microstrip antenna can be controlled. Also, Malagisi[1] has shown that a phase-shifting reflector can be built by using circular microstrip elements with shorting posts.

We have experimentally investigated the post-loading technique. For ease of experimentation, machine screws were used as removable shorting posts. A single microstrip element was made to radiate fields that are polarized horizontal linear, vertical linear, right-hand circular, or left-hand circular. Also, single elements and an eight-element array were tuned to operate over a 1.5-to-1 range of frequencies. This frequency tuning was accomplished without the serious degradation of input impedance that was observed by Kernweis and McIlvenna. A simple analytical model has been developed and used to generate useful design data for the post-loaded microstrip antennas.

More detailed discussions of these properties of microstrip antennas are referenced in the Selected Bibliography (p 29).

[1] *Carmen S. Malagisi, Electronically Scanned Microstrip Antenna Array, U.S. Patent No. 4,053,895 (11 October 1977).*

2. FREQUENCY-AGILE ANTENNA

The operating characteristics of a typical rectangular patch microstrip antenna are determined by the antenna's size and feed location and by the substrate permittivity. The antenna in figure 1, without the shorting posts, is a typical configuration designed for linear x-polarized radiation. The antenna operates at a fundamental frequency, f_o,

$$f_o \approx \frac{c}{2a\sqrt{\varepsilon_r}} \quad , \tag{1}$$

where the patch length, a, is approximately one-half wavelength in the dielectric. At this frequency, the voltage and current distributions on the patch resemble those of an open-circuited microstrip transmission line with propagation in the ± x-directions. The input impedance of the antenna is determined primarily by the patch width, b, and the feed location, f.[2]

The addition of shorting posts along the centerline, y = b/2, increases the operating frequency of the antenna. This frequency increase may be explained by considering the transmission-line model for the microstrip antenna.[3] This model is depicted in figure 2, where Z_o is the characteristic impedance of a microstrip line of width b on the substrate material. The length extensions, $\Delta\ell$, account for fringe-field reactance at the open circuit ends, and the conductance, G, accounts for radiation from the ends. The formulas of Hammerstad[4] were used to calculate Z_o and $\Delta\ell$, and Harrington's formula[5] for slot conductance was used for G.

$$Z_o = \frac{377}{\sqrt{\varepsilon_e}} \left[b/t + 1.393 + 0.667\ \ln(b/t + 1.444) \right]^{-1} \quad , \tag{2}$$

$$\Delta\ell = 0.412t\ \frac{(\varepsilon_e + 0.3)(b/t + 0.262)}{(\varepsilon_e - 0.258)(b/t + 0.813)} \quad , \tag{3}$$

[2] *Y. T. Lo, D. Solomon, and W. F. Richards, Theory and Experiment of Microstrip Antennas, IEEE Trans. Ant Prop, AP-27 (March 1979), 137-145.*

[3] *Anders G. Derneryd, Linearly Polarized Microstrip Antennas, IEEE Trans. Ant Prop AP-24 (November 1976), 846-851.*

[4] *E. O. Hammerstad, Equations for Microstrip Circuit Design, Proc. 5th European Microwave Conference (September 1975), 268-272.*

[5] *R. F. Harrington, Time-Harmonic Electromagnetic Fields, McGraw-Hill, New York (1961), 183.*

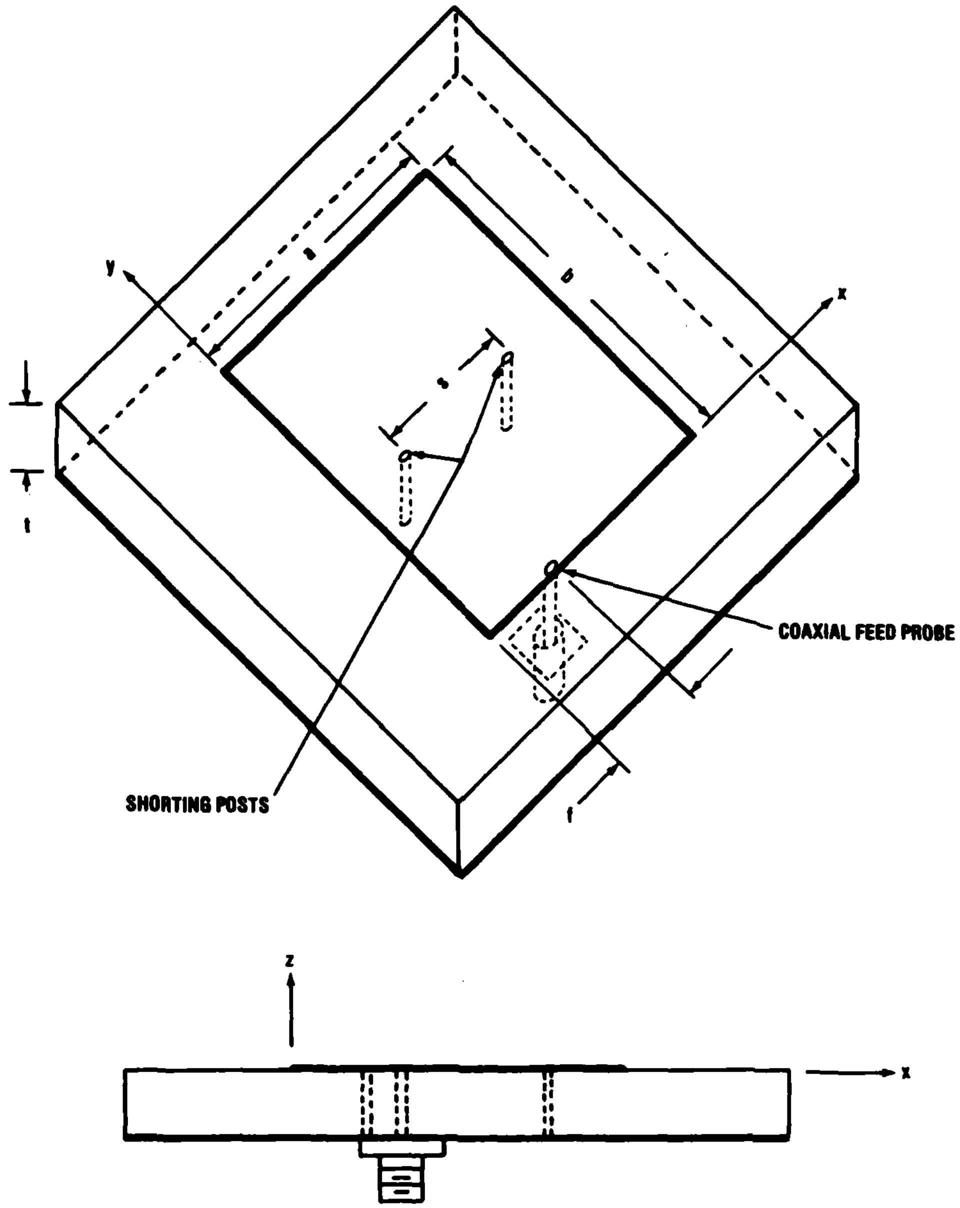


Figure 1. Typical microstrip antenna with shorting posts for changing operating frequency.

where

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2(1 + 10t/b)^{1/2}} \tag{4}$$

$$G = \frac{\pi b}{377\lambda_o}\left[1 - \frac{(kt)^2}{24}\right] \tag{5}$$

$$\approx 0.0083\ b/\lambda_o,\ t/\lambda_o << 1\ .$$

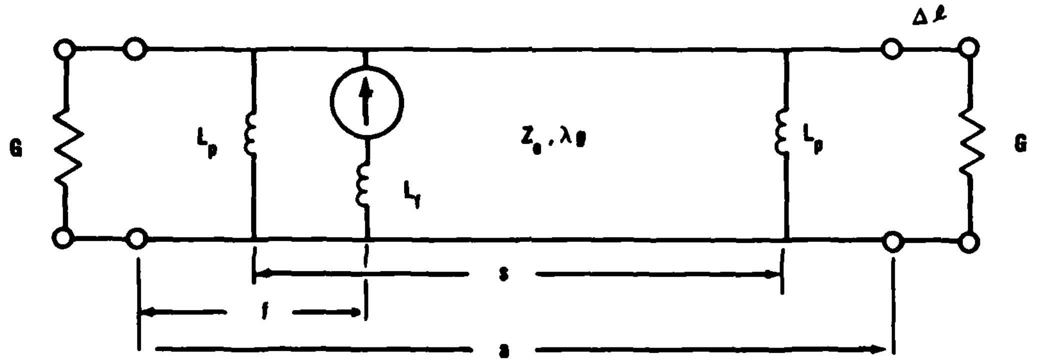


Figure 2. Transmission-line model for calculating operating frequency and input impedance of frequency-tuned antenna.

The rf feed is represented by a current source with a series inductor to represent the feed probe inductance.[6] The shorting posts are represented as shunt inductances at the locations of the posts. The inductive reactance of the posts and the feed probe is calculated from the formula,

$$X_L = \frac{377}{\sqrt{\varepsilon_r}} \tan \frac{2\pi t}{\lambda_o}\ . \tag{6}$$

The input impedance and radiation loss are calculated from this model. Plots of the operating frequency and voltage standing wave ratio (VSWR) are shown in figure 3. The agreement between the calculated and

[6] *Keith R. Carver and Edgar L. Coffey, Theoretical Investigation of the Microstrip Antenna, New Mexico State University Physical Science Laboratory, Technical Report PT-00929 (January 1979), prepared for U.S. Army Research Office Grant DAAG29-78-G-0082.*

measured results is quite good and demonstrates that this transmission-line model yields useful design data for the post-tuned microstrip antenna.

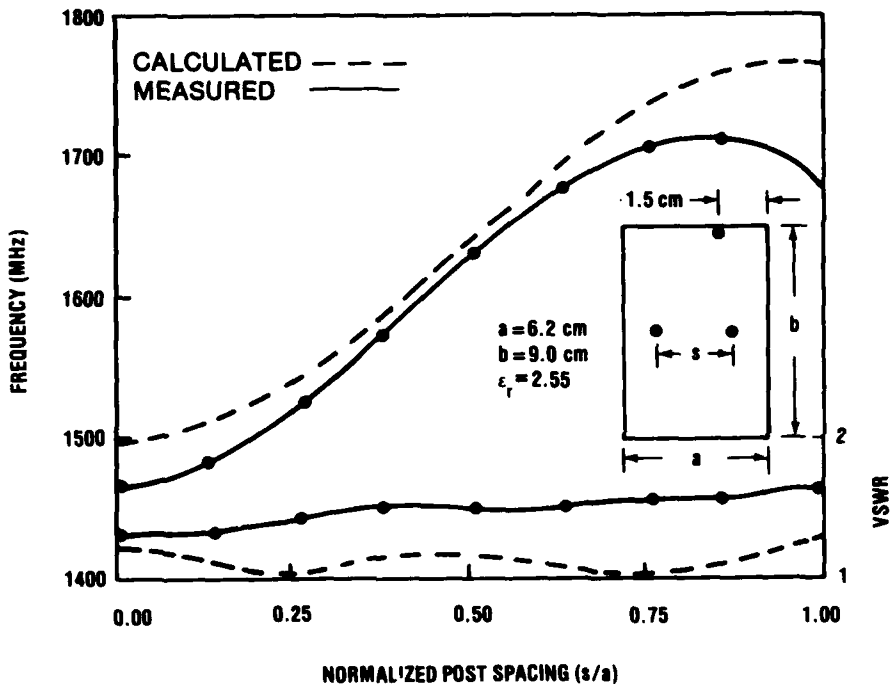


Figure 3. Operating frequency (upper curves) and VSWR (lower curves) of frequency-tuned antenna.

The range of frequency tuning achieved by a pair of posts along the centerline is about 20 percent, but tuning ranges in excess of 50 percent have been achieved by adding more posts. These additional posts may be placed along the centerline, y = b/2 (fig. 1), or offset from the centerline along y = b/2 ± c. (When placing posts away from the centerline, it is preferred that they be added in pairs symmetric about the centerline. This avoids the introduction of cross-polarized signals.) The radiation patterns in figure 4 demonstrate that the antenna's performance is not degraded by the shorting posts. The bandwidth (VSWR < 2) is approximately 1 percent at each operating frequency.

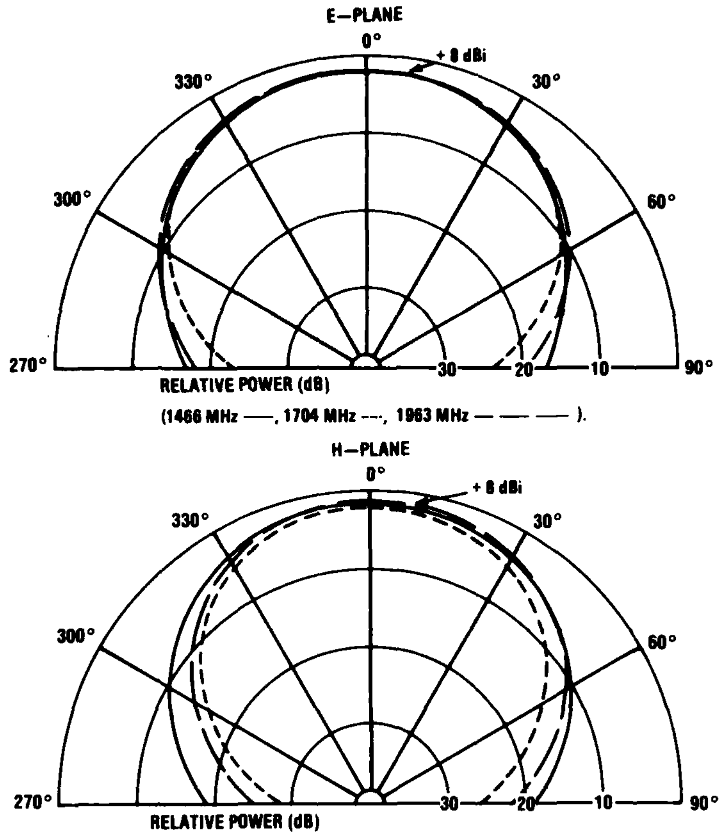


Figure 4. Typical radiation patterns of 6.2 × 9.0-cm frequency-tuned microstrip antenna on 1.6-mm Teflon fiberglass substrate. Substrate and ground plane are 22 cm square. Peak gains are approximately 8 dBi.

3. POLARIZATION DIVERSITY

The polarization of the microstrip antenna also can be selectively altered by proper location of the shorting posts.[7] Of particular interest is the square patch fed along a diagonal with shorting posts along one of the centerlines (fig. 5). This antenna will radiate x- or y-

[7] *Daniel H. Schaubert and Frederick G. Farrar, Microstrip Antenna with Polarization Diversity, Program and Abstracts of National Radio Science Meeting USNC/URSI (November 1979), 139.*

oriented linear polarization, or right- or left-circular polarization, depending upon the locations of the posts. Typical radiation patterns obtained by using a spinning, linearly polarized receive antenna are shown in figures 6 and 7. The antenna configuration in figure 6 is linearly polarized. The pattern shapes are different because figure 6(a) is an E-plane pattern cut and figure 6(b) is an H-plane pattern cut. In figure 7, the antenna is configured for circular polarization. The axial ratio is less than 3 dB over a wide sector around the zenith. (The axial ratio does not become infinite at the horizon because the ground plane is relatively small.)

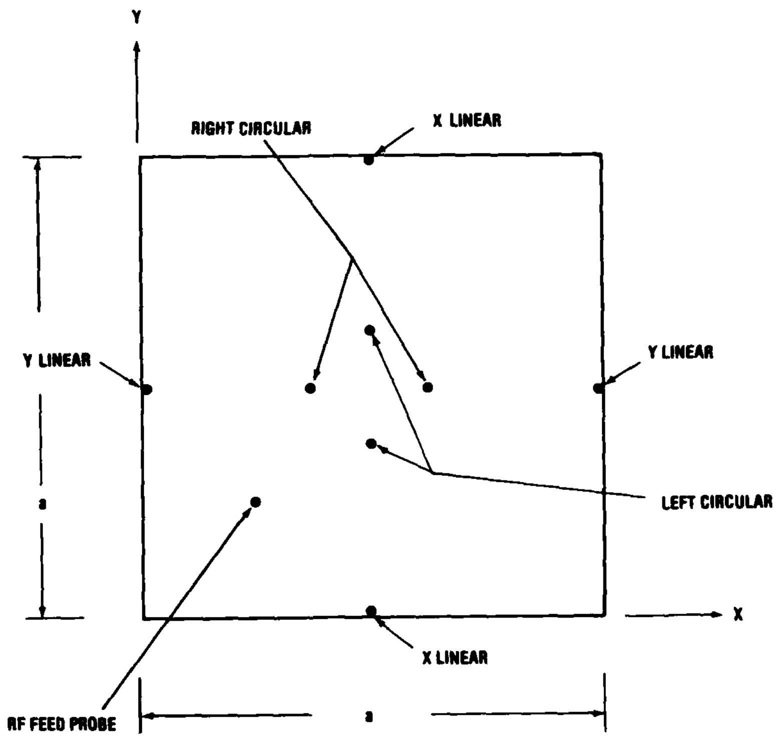


Figure 5. Square-patch antenna with four pairs of posts for obtaining four different polarizations.

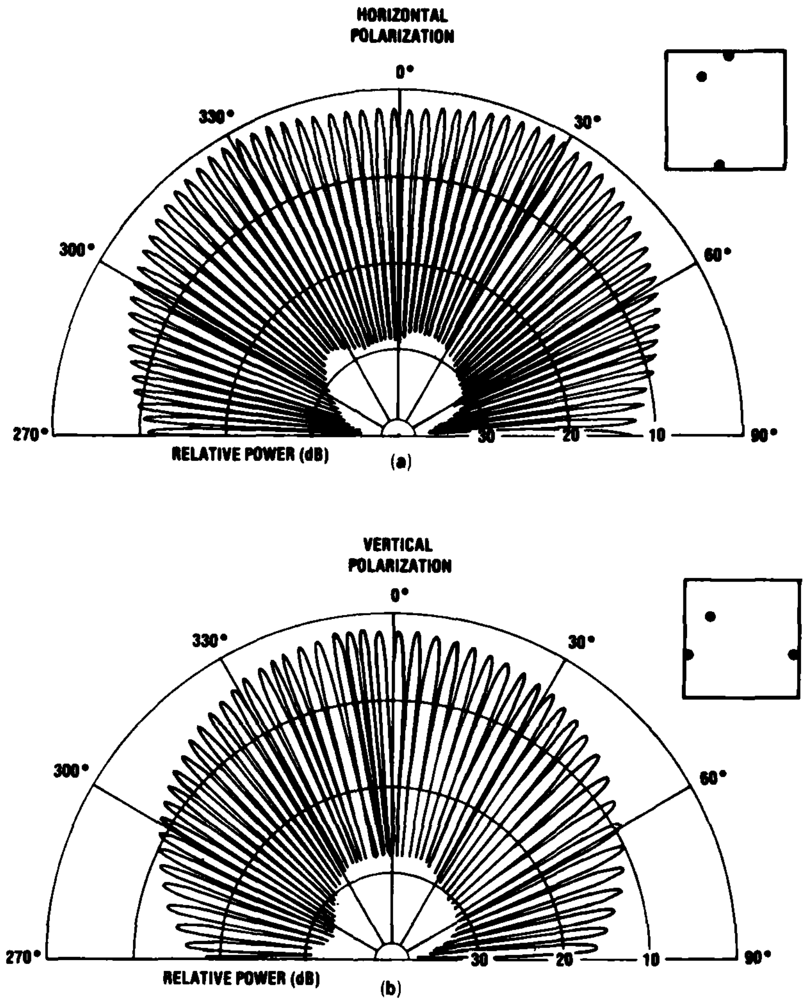
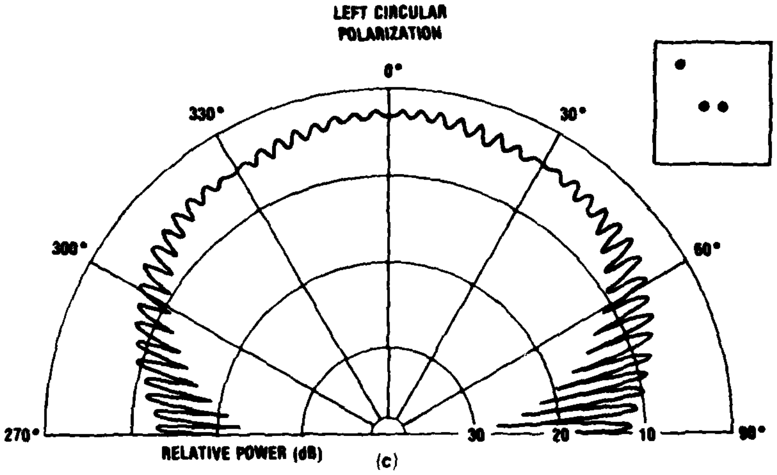


Figure 6. Typical spin-linear radiation patterns of 6.2-cm square patch in horizontal and vertical polarized configurations. Substrate and ground plane are 22 cm square.



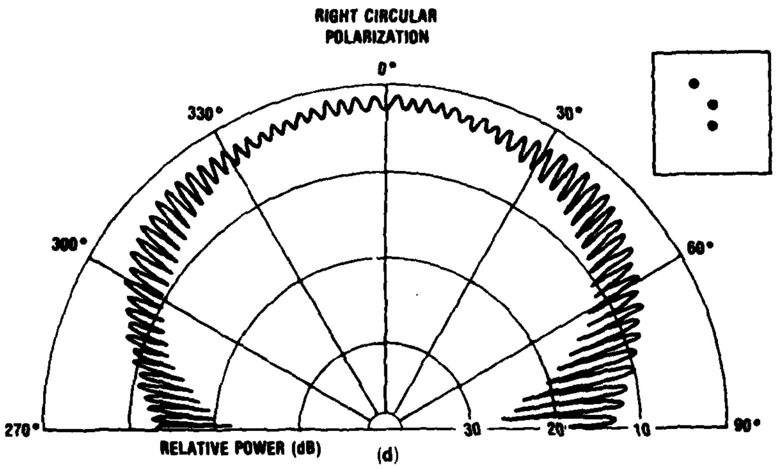


Figure 7. Typical spin-linear radiation patterns of 6.2-cm square patch in left-circular and right-circular polarized configurations.

These polarization changes can be explained by considering the frequency-tuning effects described above. The square patch without shorting posts supports both x-oriented and y-oriented modes, which have the same resonant frequency. Since the feed probe is located on the diagonal of the patch, both the x- and y-oriented modes are excited with equal amplitude and phase. By adding shorting posts along the center-

line x = a/2 (fig. 5), the resonant frequency of the y-oriented mode can be raised without affecting the x-oriented mode. Similarly, by adding posts along y = a/2, the resonant frequency of the x-oriented mode can be raised without affecting the y-oriented mode. Therefore, a single mode (x- or y-oriented) may be selected by shifting the resonant frequency of the undesired mode far above that of the desired mode. This large frequency shift is obtained by placing shorting posts at or near the edges of the patch. The result is linear polarization.

Circular polarization may be obtained by exciting both the x- and y-oriented modes with equal amplitudes, but with 90-deg phase difference. This can be accomplished by raising the resonant frequency of one mode slightly above the other and operating at a frequency between the two resonances. Then the input impedance of one mode is inductive and the other mode is capacitive. By adjusting the difference between the resonant frequencies, both modes can be excited with equal amplitudes and a 90-deg phase difference.

Figure 8 shows the measured axial ratio of a typical antenna as the separation between a pair of shorting posts is changed. When s/a = 0, the posts are at the center and they do not affect either mode. In this case, the antenna is linearly polarized along the diagonal with the feed. When s/a = 0.09, the resonant frequencies of the two modes are offset enough to create a phase difference of approximately 90 deg, and the antenna is circularly polarized. As the posts are moved further apart, the resonant frequency of the vertical mode is further increased and the antenna's polarization becomes horizontal linear. The input impedance of the antenna changes as the posts are moved, but the VSWR remains very good for all senses of polarization. (Although the best circular polarization occurs at a frequency slightly above the resonance for the linear polarization, the bandwidth of the linearly polarized antenna is adequate to permit it to operate at the same frequency as the circularly polarized antenna.)

4. OTHER CONFIGURATIONS

Several alternative configurations of the frequency-agile and polarization-diverse antennas have been designed, built, and tested. These alternative configurations are useful because they increase the versatility of the post-tuned microstrip antenna.

4.1 Circular Microstrip Antenna

Circular microstrip antennas perform well as polarization-diverse radiators. The antenna depicted in figure 9 can provide all four types of polarization, as shown in figure 10. The 6.2-cm-diam

antenna's performance is similar to that of a 5.3-cm square antenna, which would operate at 1724 MHz and would occupy approximately the same surface area.

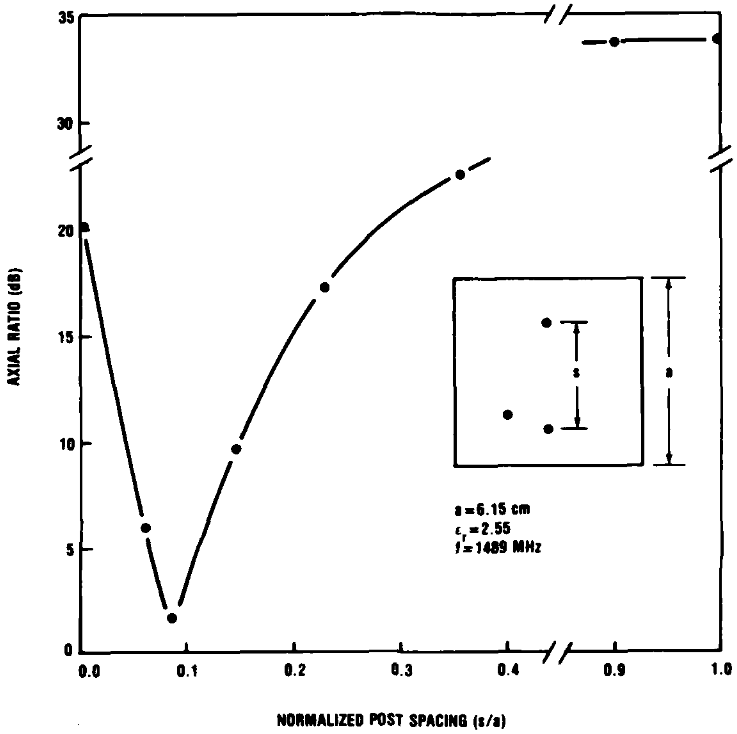


Figure 8. Measured axial ratio of 6.15-cm square patch antenna with a pair of symmetrically located posts.

4.2 Simple, Polarization-Diverse Configuration

A particularly simple form of the polarization-diverse antenna with only two polarization states can be implemented as shown in figure 11. A positive or negative dc bias can be inserted through the rf feed to select the desired polarization. Two orthogonal, linear polarizations are obtained from the antenna in figure 11, but any combination of two polarizations can be obtained by properly locating the diodes.

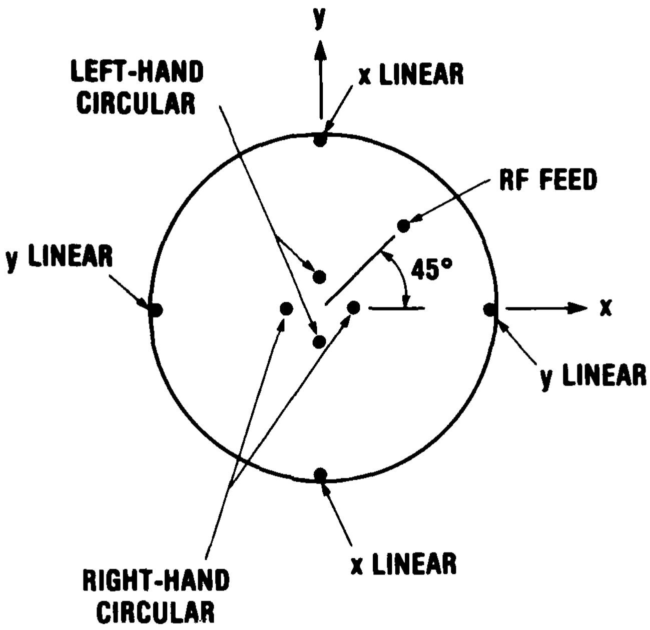


Figure 9. Circular microstrip antenna with posts for polarization diversity.

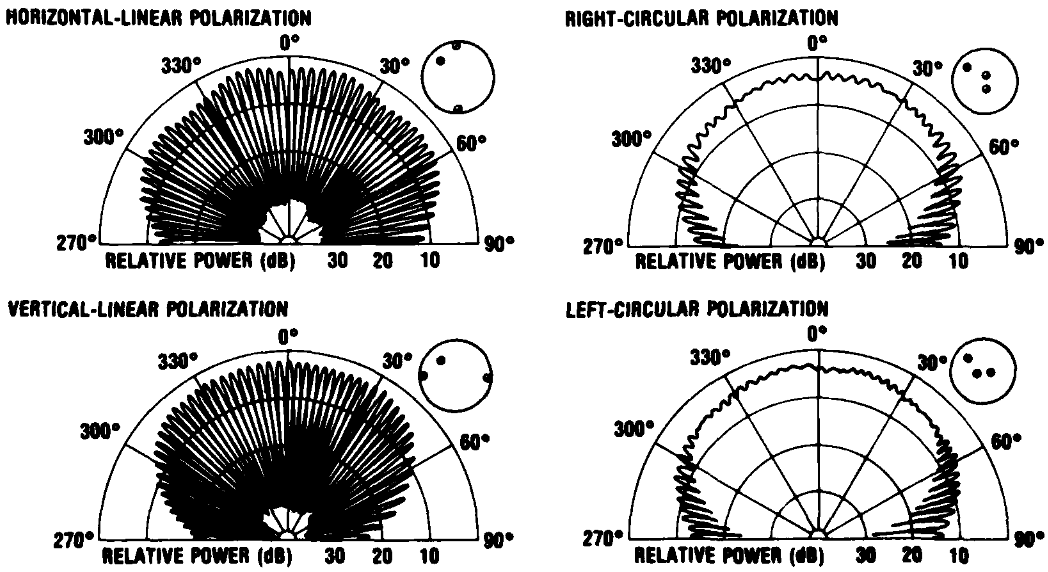


Figure 10. Typical spin-linear radiation patterns of circular microstrip antenna.

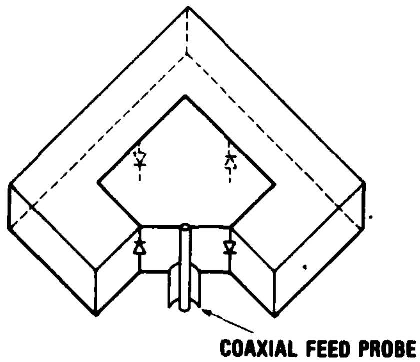


Figure 11. Simple, polarization-diverse antenna designed for bias insertion through rf feed.

4.3 Centerline-Fed Antennas

Another form of polarization-diverse antennas is square patches fed along a centerline. These patches (fig. 12(a)) provide one linear polarization (no posts) and both circular polarizations by means of shorting posts located along the diagonals of the patch. The addition of a second feed (fig. 12(b)) permits simultaneous operation in two polarizations. A dual-feed, 6.2-cm square patch with coaxial probe feeds demonstrated dual polarization performance with greater than 30-dB isolation between the two linear polarizations and greater than 20-dB isolation between the two circular polarizations.

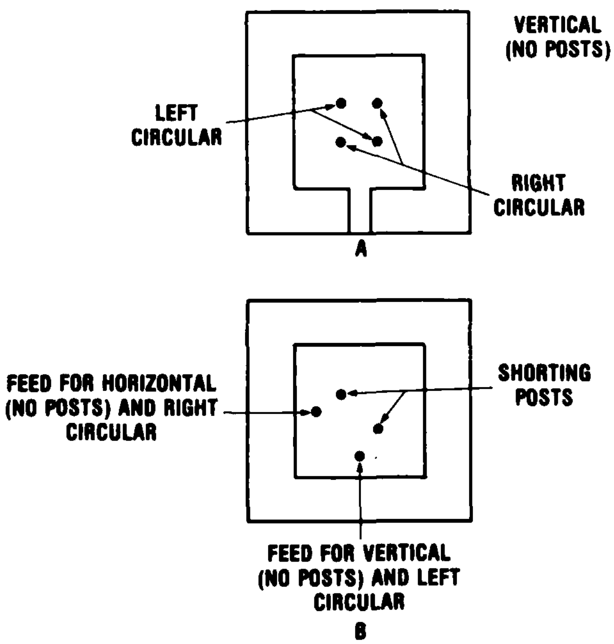


Figure 12. Centerline-fed, polarization-diverse antennas: (a) three-polarization antenna, (b) switchable, dual-polarization antenna.

4.4 Single- and Multiple-Post Antennas

The frequency tuning and polarization control described above use pairs of posts. Similar results can be obtained by using only one post or more than two posts. Figure 13 shows the measured axial ratio of a diagonal-fed square patch with a single post. The axial ratio is essentially the same for the post located either near or opposite the feed probe. Circular polarization (2-dB axial ratio) is obtained when the single post is approximately twice as far from the center as when a pair of posts is used (see fig. 8).

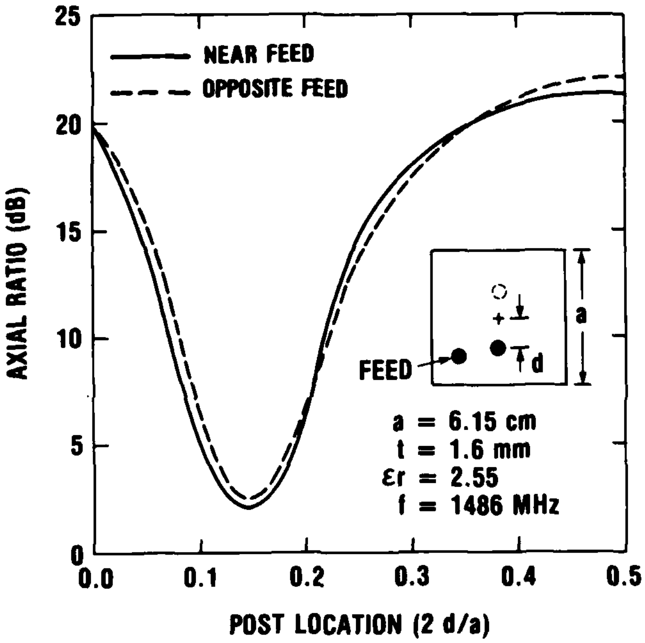


Figure 13. Measured axial ratio of antenna with one post near the feed and one post opposite the feed.

The frequency-tuning effects of a single post are shown in figure 14. The total tuning range is less than for a pair of posts and the VSWR varies more.

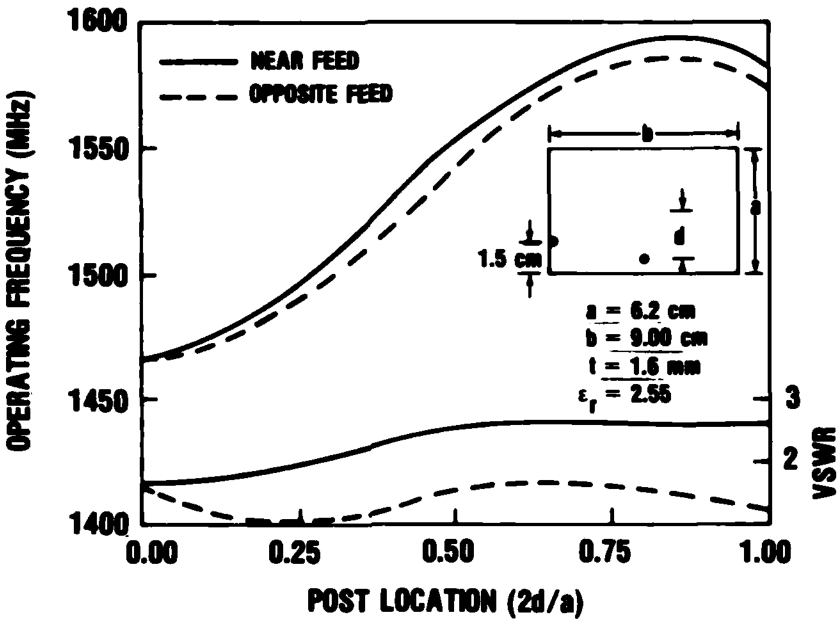


Figure 14. Measured operating frequency and VSWR of antenna with one post near the feed and one post opposite the feed.

The maximum frequency of the 6.2- × 9.0-cm antenna with a pair of posts is 1711 MHz (fig. 3). By using more posts, this maximum frequency can be increased to 2120 MHz. Figure 15 shows the measured operating frequency of the 6.2- × 9.0-cm patch for a variety of post locations. The VSWR and radiation patterns are good at all frequencies. Attempts to increase the operating frequency beyond 2120 MHz by changing the number and location of the posts have resulted in a deterioration of the impedance match. Therefore, the useful operating frequency range of this antenna is 1466 to 2120 MHz.

4.5 Antennas with More Posts and Less Conductor

Since the length of the post-tuned, frequency-agile antenna must be one-half wavelength at the lowest frequency in its tuning range, it is longer than a standard microstrip antenna designed for the highest frequency. This can create a problem in arrays of frequency-agile antennas, because the element size limits the minimum element spacing and, therefore, controls the locations of the grating lobes. However, this problem can be alleviated by combining the post tuning with Kerr's technique (listed in Selected Bibliography) of removing a portion of the conducting patch in order to lower the operating frequency. An element of this type is depicted in figure 16. Without posts, this antenna

operates at 1166 MHz, 20 percent below the frequency of a standard 6.2-cm-long patch. With posts in the indicated positions, the antenna operates at 1675 MHz, which represents a frequency-tuning range of 1.4 to 1.

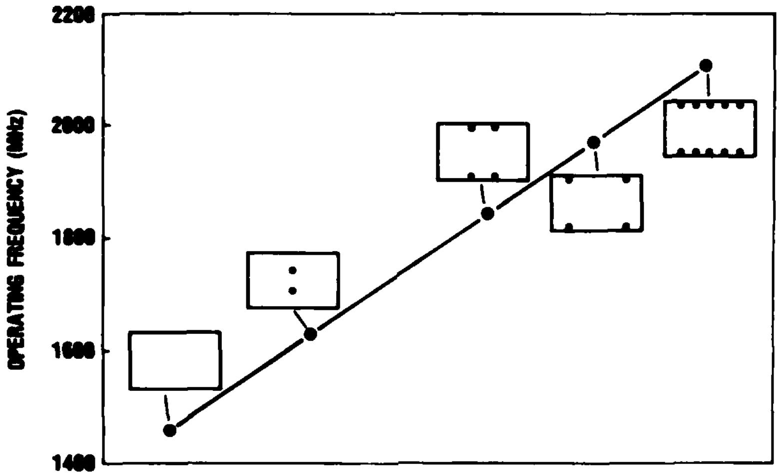


Figure 15. Operating frequency of 6.2- × 9.0-cm antenna (1.6-mm Teflon fiberglass substrate) for various post configurations.

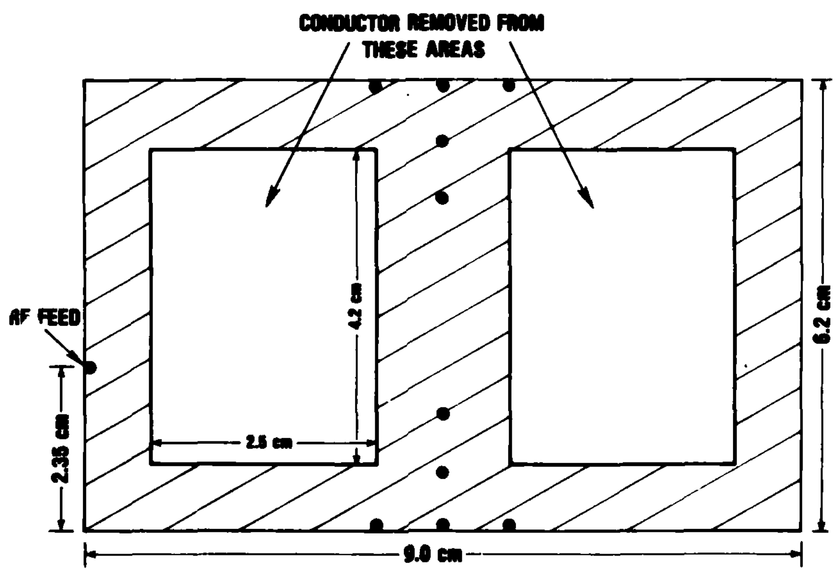


Figure 16. Rectangular microstrip antenna with a portion of conductor removed to lower fundamental frequency and posts added to tune frequency upward.

The input impedance and radiation patterns of this modified antenna are generally good across its entire frequency range. However, the radiation pattern sometimes deteriorates due to the presence of another radiation mode. This mode is present in most of the microstrip antennas, but it usually occurs at a frequency that is significantly different from that of the desired radiation mode. The two different radiation modes are shown in figure 17. Figure 18 shows the radiation pattern of the antenna for a post configuration that supports both the desired radiation mode and the additional mode at 1675 MHz. The combination of these modes produces a tilted beam that may be undesirable. (On the other hand, this tilted beam can be useful for some applications.) Nonetheless, the antenna can be configured to suppress the undesired mode and yield a nearly symmetric radiation pattern at 1675 MHz (fig. 19), or at any other frequency within its tuning range.

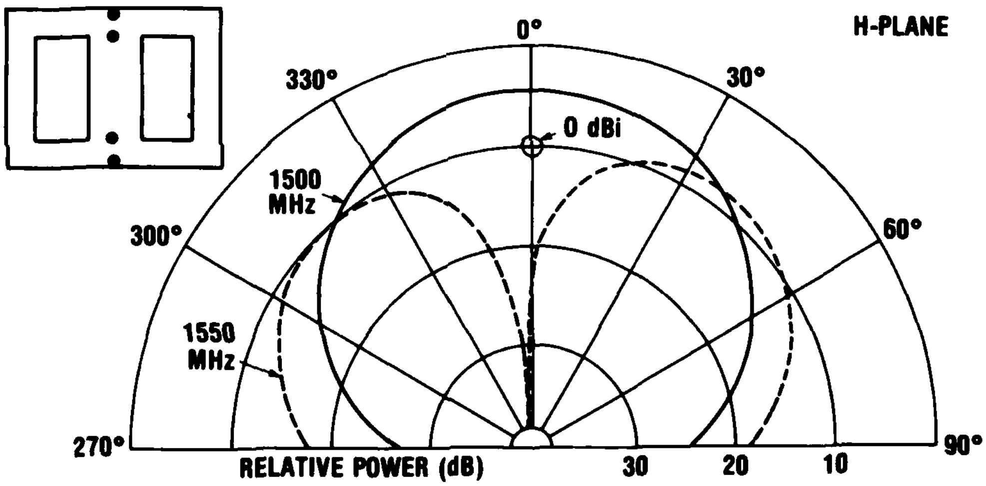


Figure 17. Two modes of radiation for 6.2- × 9.0-cm modified antenna.

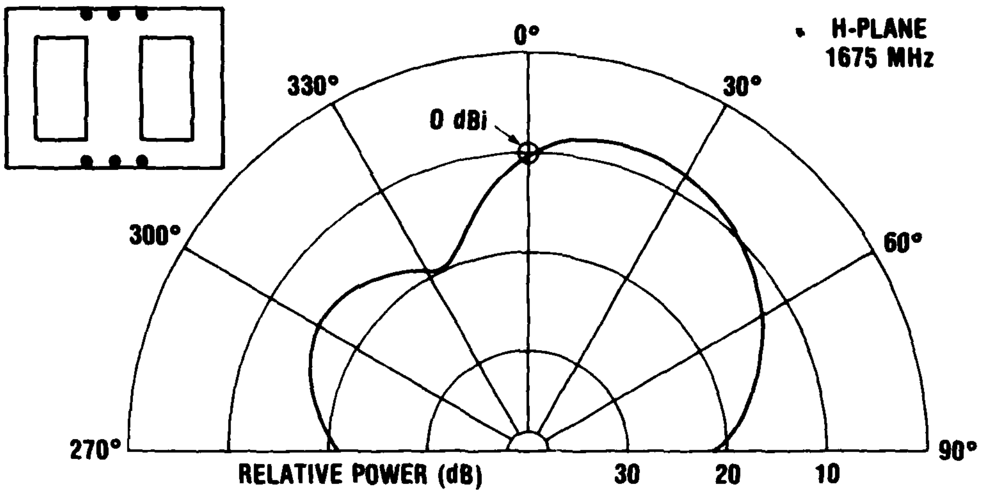


Figure 18. Tilted radiation pattern of 6.2- × 9.0-cm modified antenna in configuration that supports two modes.

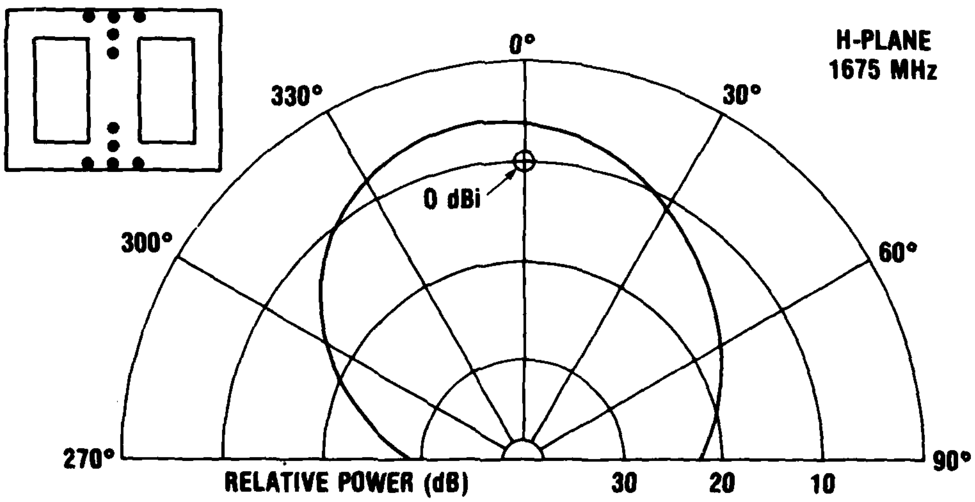


Figure 19. Radiation pattern of 6.2- × 9.0-cm modified antenna with posts located as shown in figure 16.

4.6 Other Potential Configurations

Other potential configurations of the post-tuned antennas include a frequency-agile, one-quarter-wavelength antenna (fig. 20) and a frequency-agile antenna with polarization diversity. This latter type of antenna could be implemented by feeding a square microstrip along its diagonal and locating shorting posts at various positions along the two centerlines (fig. 21). Since the posts along $x = a/2$ affect only the y-oriented modes and the posts along $y = a/2$ affect only the x-oriented modes, post locations may be selected to obtain (1) one of these linearly polarized modes at each specified frequency or (2) both of the modes with the correct amplitude and phase for circular polarization at each frequency. Of course, many different posts are needed in order to obtain all polarizations at several different frequencies.

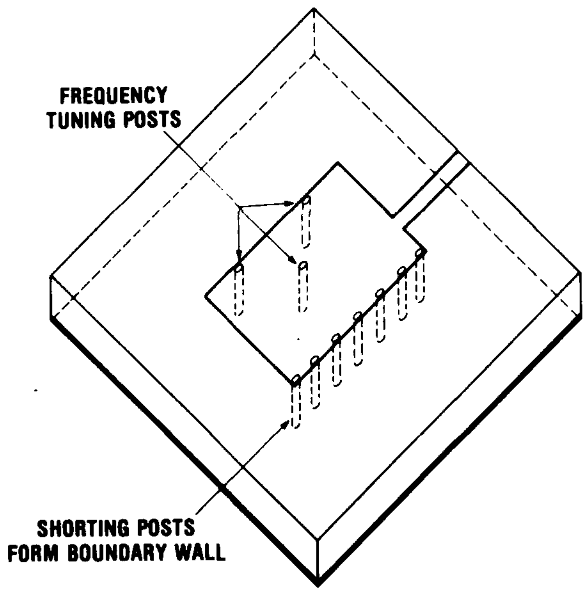


Figure 20. One-quarter-wavelength microstrip antenna with frequency tuning posts.

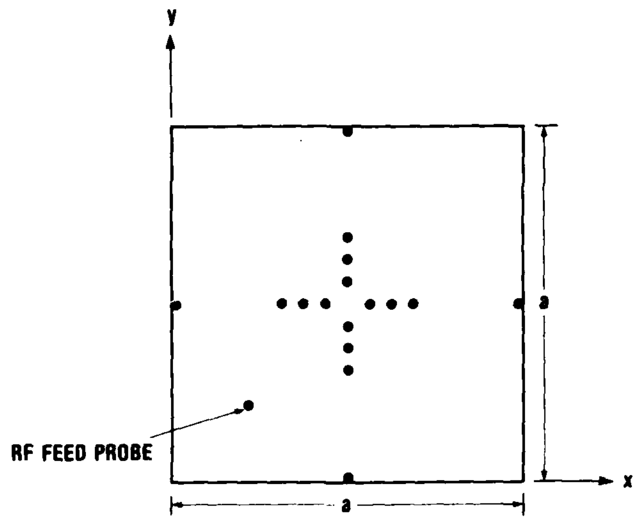


Figure 21. Microstrip antenna with multiple post locations to provide both frequency agility and polarization diversity.

5. FREQUENCY-SCANNED ARRAY

Thin, conformal, frequency-scanned arrays can also be built with the frequency-agile microstrip antenna. An eight-element linear array consisting of 4.32- × 6.16-cm patches has been fabricated on 1.6-mm (1/16-in.) thick Teflon fiberglass substrate. This experimental array (fig. 22) is tuned with small machine screws inserted into holes in the antennas. A corporate feed network that provides progressive phase shift was used to create an antenna that scans ±45 degrees from broadside as the frequency varies from 2.08 to 2.89 GHz (fig. 23). This type of antenna with diode tuning posts would perform well in a computer-controlled system that simultaneously increments the operating frequency of the antenna and the transmitter/receiver.

6. CONCLUSIONS

The operating frequency and polarization of microstrip antennas can be conveniently controlled by inserting shorting posts at appropriate locations within the antenna's boundary. From the use of microwave

switching diodes, an electronically controlled frequency-agile or polarization-diverse antenna can be obtained.

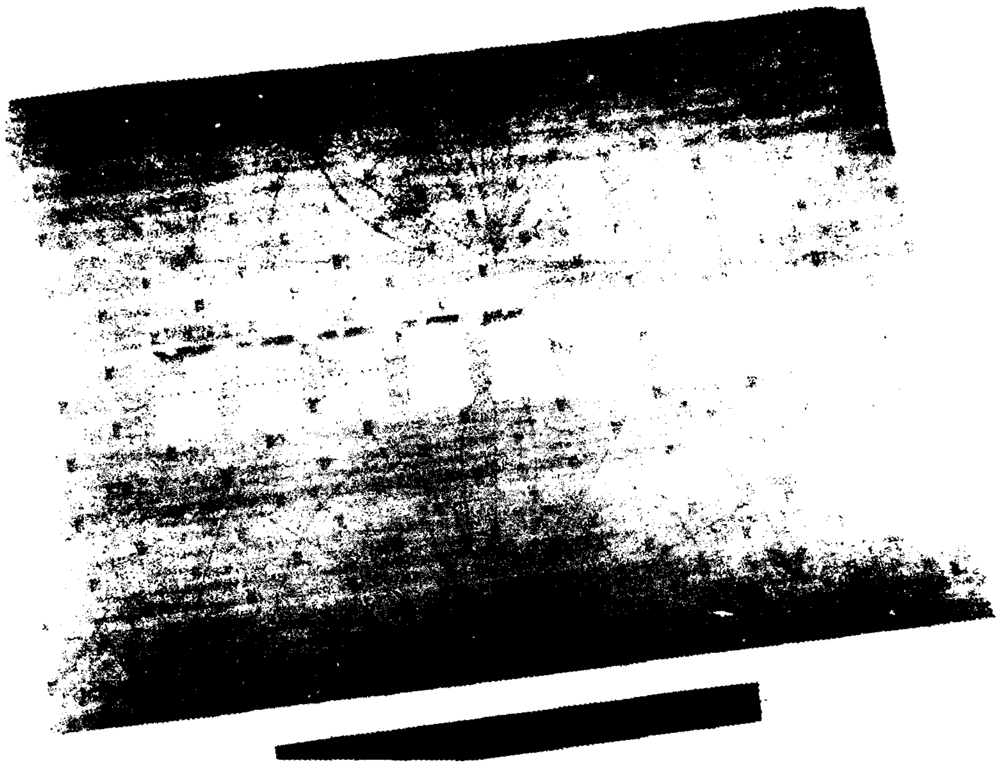


Figure 22. Prototype array of post-tuned elements for frequency-scanned applications.

The operating frequency of a rectangular microstrip antenna can be tuned over a 1.5-to-1 range without changing its size or the feed location. The tuning is accomplished by varying the number and locations of the shorting posts. The radiation patterns of the microstrip elements do not change significantly as the operating frequency is varied.

This method of tuning eliminates most of the temperature drift and bias-control problems that are encountered if varactors are used to tune the antenna's operating frequency. Also, since the frequency depends on post locations and not on variable reactances, it should be easier to ensure that all elements of an array are resonant at the same frequency.

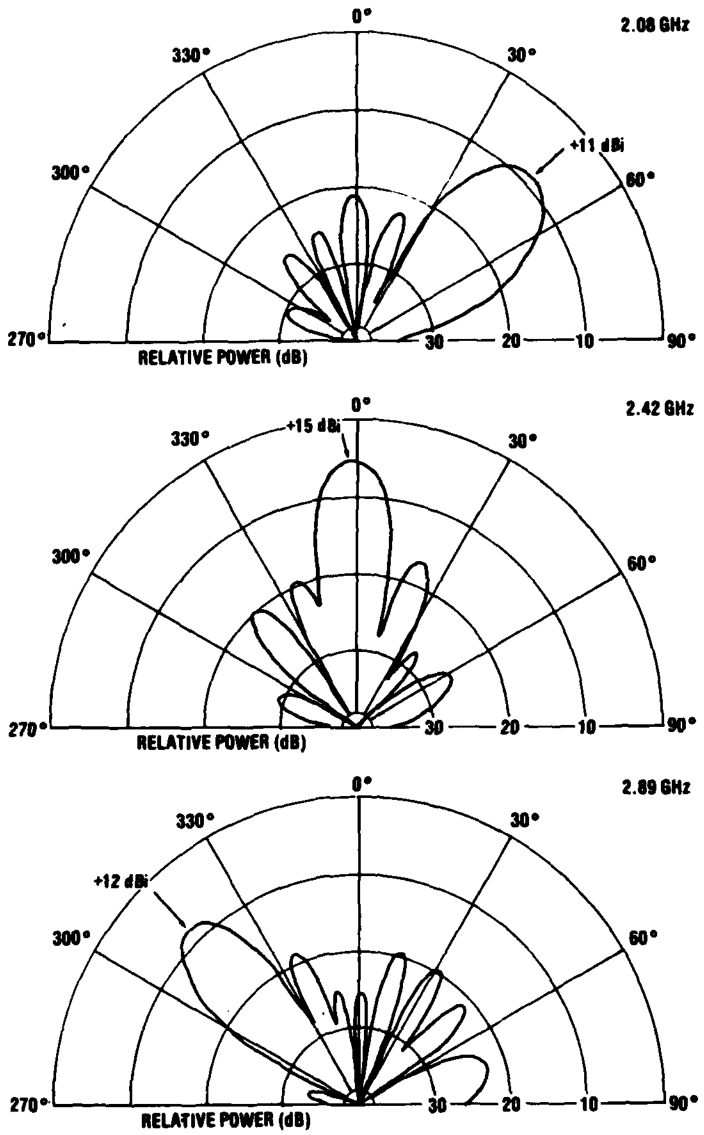


Figure 23. Typical E-plane radiation patterns of eight-element, frequency-scanned array with uniform amplitude distribution. Array gain is 11 dBi at 2.08 GHz, 15 dBi at 2.42 GHz, and 12 dBi at 2.89 GHz.

The polarization of square microstrip antennas can be varied by changing the locations of shorting posts. Very narrow bandwidth circular polarization of either sense can be obtained, as well as horizontal or vertical linear polarization. The axial ratio of the circularly polarized antenna is less than 3 dB over a wide portion of the beam. Similar results have also been obtained for circular microstrip antennas.

In addition to providing active control of the frequency and polarization of a microstrip antenna, these post-tuning techniques can ease the burdens on designing and manufacturing the antennas. The precise operating frequency and polarization can be altered by inserting shorting posts during manufacturing or prior to use in order to obtain the desired performance.

The frequency agility and polarization diversity provide added versatility to the microstrip antenna. Furthermore, these features are obtained without sacrificing the thin, conformal structure of the microstrip antenna and without increasing the complexity of the external of microwave feed network.

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